

# BUILDING A SAMPLE OF DISTANT CLUSTERS OF GALAXIES

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**Abstract.** Candidate clusters of galaxies drawn from the sample identified from the moderately deep  $I$ -band data of the ESO Imaging Survey (EIS), have been used for follow-up optical/infrared imaging and spectroscopic observations. The observations were conducted to assess the nature of these candidates over a large range of redshifts. Currently, 163 EIS candidates have  $(V - I)$  colors, 15 have  $(I - K)$  and 65 cluster fields have been observed spectroscopically. From a preliminary analysis of these data, we find that  $> 65\%$  of the candidates studied show strong evidence of being real physical associations, over the redshift range  $0.2 < z < 1.1$ . The evidence in some cases comes directly from spectroscopic measurements, in others indirectly from the detection of overdensities of objects with either the same color or the same photometric redshift, or from a combination of color and spectroscopic information. Preliminary results also suggest that the redshift derived from the matched-filter algorithm is a reasonable measure of the cluster's redshift, possibly overestimating it by  $\Delta z \sim 0.1$ , at least for systems at  $z < 0.7$ . Overdensities of red objects have been detected in over 100 candidates, 38 of which with estimated redshifts  $> 0.6$ , and six candidates in the interval  $0.45 < z < 0.81$  have either been identified directly from measured redshifts or have been confirmed by the measurement of at least one redshift for galaxies located along a red-sequence typical of cluster early-type galaxies. Lastly, five candidates among those already observed in the infrared have  $(I - K_s)$  colors consistent with them being in the redshift interval  $0.8 < z < 1.1$ . The sample of "confirmed" clusters, already the largest of its kind in the southern hemisphere, will be further enlarged by ongoing observations.

## 1 Introduction

The recent discovery of apparently massive and relaxed clusters of galaxies at redshifts  $z \gtrsim 0.5$  offers a unique opportunity to study the evolution of gravitationally bound systems over an extended look-back time. Moreover, if such systems are proven to be massive, especially those at  $z \gtrsim 0.8$ , their sheer existence can impose stringent constraints on viable cosmological models [2] [8]. In addition, a large sample of confirmed clusters, spanning a broad redshift range, is of great interest for constraining models of formation and evolution of early-type galaxies and large-scale structure, and for the selection of targets in different redshift intervals for a variety of other applications. While the existence of high-redshift clusters is

by now generally accepted, current samples of spectroscopically confirmed clusters, predominantly  $X$ -ray selected, are small and unlikely to grow in the near future, at least not until deep observations with Chandra and XMM are carried out and analyzed. This is particularly true at the highest redshifts ( $z \sim 1$ ), where only a handful of systems have been confirmed so far [17] [20] [18].

An alternative approach is to use moderately deep  $I$ -band surveys to identify overdensities in the projected distribution of galaxies. Surveys suitable for this purpose include the Palomar Distant Cluster Survey [15], covering over 5 square degrees in the northern hemisphere, and the ESO Imaging Survey (EIS) [12] [13] [21], covering about 17 square degrees in the southern hemisphere. The main advantage of optical searches is that large areas of the sky can be covered using wide-field imagers. However, the yield of physical associations from such samples is largely undetermined, as projection, among other effects, may lead to spurious detections. Therefore, assessing the success rate of the identification of real systems at different redshifts is an essential step in determining the possible role, and the best design, of ground-based wide-angle surveys in building a large sample of confirmed clusters over a large redshift range suitable for evolutionary studies.

In this contribution, we describe the ongoing effort to establish the yield of real clusters from the EIS distant cluster candidate list. To this end we combine the results obtained from follow-up observations by different groups. This ongoing work includes optical/infrared imaging and spectroscopic observations, which are used to provide either direct or circumstantial evidence supporting the identification of real systems. The confirmation of a cluster candidate requires one or more of the following conditions: the identification of concordant redshifts from spectroscopic observations; the existence of a distinctive red-sequence in optical/infrared color-magnitude diagrams; the detection of a statistically significant concentration of galaxies with similar colors or photometric redshifts.

## 2 Analysis of Photometric Data

The original EIS catalog of cluster candidates was constructed by applying a matched-filter algorithm [15] to galaxy catalogs extracted from the EIS  $I$ -band survey images [10] [16] [3]. The survey covers four patches of the sky spread over the right ascension range  $22^h \lesssim \alpha \lesssim 10^h$  and the object catalogs reach a limiting magnitude of  $I_{AB} \sim 23$ . Details about these data, the location of the patches and the EIS cluster candidate catalog can be found in the original papers [12] [13] [21]. More recently, most of the area covered by the  $I$ -band survey has been observed in  $B$  and  $V$  as part of the public survey being conducted by EIS using the wide-field camera now available at the MPG/ESO 2.2m telescope at La Silla [6] [11]. A summary of the data currently available, combining these new data with those in the  $B$  and  $V$  passbands of the original survey [16], is shown in Table 1. The table gives, for each EIS patch, the total area covered in each passband. The survey is still ongoing and it is expected to cover roughly 14 square degrees in  $BVI$ .

Table 1: **Wide-Angle Survey (square degrees)**

Patch	U	B	V	I
A	-	1.0	1.2	3.2
B	1.25	1.5	1.5	1.6
C	-	6.0	-	6.0
D	-	6.0	6.0	6.0
Total	1.25	14.5	8.7	16.8

The available data provide color information for a significant fraction of the EIS cluster candidates. Nearly all candidates already have  $BI$  and over half of them have  $BVI$  data.

Also available are data obtained by different groups from optical/infrared observations of EIS cluster candidates with  $z > 0.5$ . These data were obtained at the NTT [22] (infrared observations for 15 clusters) and the Danish 1.5m telescope on La Silla, and the Nordic Optical Telescope [14] ( $V$  and  $R$  observations for 50 clusters). These observations are still ongoing, which will enable doubling the sample within the next year.

## 2.1 The red-sequence of early-type galaxies

Even though there is no substitute for direct spectroscopic confirmation of candidate cluster of galaxies, these observations are extremely time consuming. In fact, for this type of work it is not only important to have a high-confidence that the selected candidates are real associations but also to be able to select individual galaxies likely to be cluster members.

One way of pre-selecting candidates is to use the available multi-color data to search for galaxies with red colors corresponding to the cluster early-type galaxy population. Such red-sequences have been detected over a broad redshift range using optical and optical/infrared colors for low and high redshift clusters, respectively [9] [20]. As shown below, from the data we have, optical colors are useful for  $z \lesssim 0.7$ , while optical/infrared data are required to extend the redshift range beyond this limit.

In order to find supporting evidence that the EIS candidates are physical associations, those with available data in the  $V$  and  $I$  filters have been analyzed to search for the presence of a red-sequence. This has been done either by direct inspection of the  $(V - I) - I$  color-magnitude diagrams where, at least for clusters with  $z \lesssim 0.4$ , a red-sequence appears as a distinctive feature[13], or by evaluating the statistical significance of spatial concentrations of galaxies in different color

slices. The significance of a detection is determined using mock catalogs containing the same number of objects as the data, as described in more detail in forthcoming papers [14] [22].

Considering the 105 detections at the 95% confidence level obtained from the color-slice analysis we show, in the left panel of Figure 1, the relation between the  $(V - I)$  color characterizing the detected concentrations and the redshift. For the EIS candidates we take the redshift to be  $z_{MF}$  as given by the matched-filter. For  $z \lesssim 0.7$  we show the median and the quartiles of the color distribution of the detected red galaxy concentrations. At higher redshifts, the error bars represent the full range of colors covered by the detections using deeper  $V$  data. Also shown are curves corresponding to the expected variation of the  $(V - I)$  color with redshift for a non-evolving elliptical galaxy and a passively evolving one, assuming a formation epoch at  $z > 4$ , a single burst of star formation, and a subsequent evolution in a low-density cosmological model. The colors of early-type galaxies along the red-sequence of spectroscopically confirmed clusters are also shown [20] [9].

From the figure we find that  $z_{MF}$  is by and large a fair indicator of the cluster redshift, albeit the large scatter, predicting colors consistent with the models and empirical data. The scatter in color is to a large extent due to the uncertainties in the detection procedure, errors in the galaxy colors and the uncertainties associated with  $z_{MF}$ . The consistency between the medians of the EIS candidate colors, the models and the empirical data up to  $z \lesssim 0.7$  is remarkable. For larger redshifts most cluster candidates are bluer than expected for their estimated redshift. From the visual inspection of these candidates (in different passbands) we find that the blue colors are either due to contamination by a foreground cluster or they simply reflect the fact that galaxies in high-redshift clusters are not detected in the  $V$ -band. These results show that the effectiveness of the  $(V - I)$  color in confirming cluster candidates is in practice limited to systems with  $z \lesssim 0.7$ , with deeper  $V$  data providing little additional leverage.

We have also examined the CM-diagrams based on the available optical/infrared data for 15 clusters with  $z_{MF} \gtrsim 0.6$ . From the analysis of  $(I - Ks)$  color slices, significant overdensities are detected near the nominal center of the candidates in 10 of the observed fields. The same systems are also identified in  $(J - Ks)$ , but the weak dependence of this color on the redshift yields no independent constraint on the redshift. For the  $>95\%$  confidence level detections, the colors range from about 2.4 to 3.6 for  $(I - Ks)$  and 1.6 to 2.1 in  $(J - Ks)$ . The dependence of the  $(I - Ks)$  color of cluster galaxies on redshift is shown in the right panel of Figure 1. For comparison we also show the expected dependence of the  $(I - Ks)$  color of ellipticals on redshift, for the same models presented earlier, and the color-redshift relation for clusters observed spectroscopically [20] [18]. Given the small number of candidates considered, we show the color of each detected candidate. The number in parenthesis indicates cases of overlap. While for low redshifts this color is a poor redshift indicator, it does give some leverage for redshifts  $z \gtrsim 0.7$ . Note, in particular, that the colors of the EIS candidates are at least consistent with their

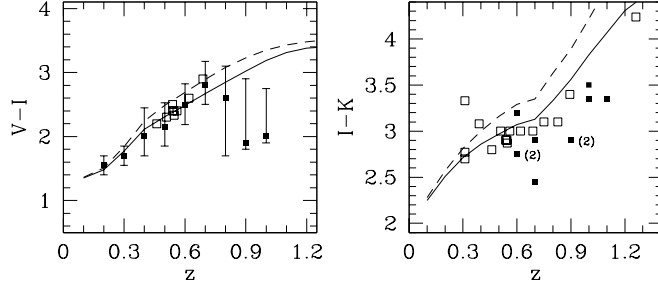


Figure 1: The relation between the median (left panel) or individual (right panel) color and redshift for the clusters detected by the color-slice analysis (solid squares). Also shown are model predictions for a non-evolving elliptical galaxy (dashed line) and a passively evolving one (solid line), and colors of cluster galaxies in spectroscopically confirmed clusters (open squares). For the EIS clusters the redshift is assumed to be that estimated by the matched-filter algorithm.

estimated redshifts and the general trend of the theoretical models, with a few cases having colors consistent with  $z \sim 1$ .

## 2.2 Photometric Redshifts

An alternative approach for testing the reality of candidate clusters is to resort to photometric redshifts. The main advantages are that the method makes optimal use of the multi-color data and that it enables one to consider not only early-type galaxies but the whole range of SEDs. Tests carried out with EIS-deep data have demonstrated [4] that the minimal set of filters required to obtain reasonable estimates of redshifts, taking into account the redshift range of interest and the limiting magnitudes in the various colors, is composed of *BVIJK*. Currently, we have such a five-band coverage for 14 clusters. Photometric redshifts have been assigned [1][4], for all galaxies brighter than  $I = 22$  within a  $5 \times 5$  arcmin field of the SOFI detector. The redshift distribution in the field of one of the candidates considered is shown in Figure 2, where it is compared to the background redshift distribution as measured from all the available fields. As can be seen the background distribution peaks at  $z \sim 0.6$ , while for the field considered the redshift distribution peaks at  $z \sim 1$ . To evaluate the significance of these peaks

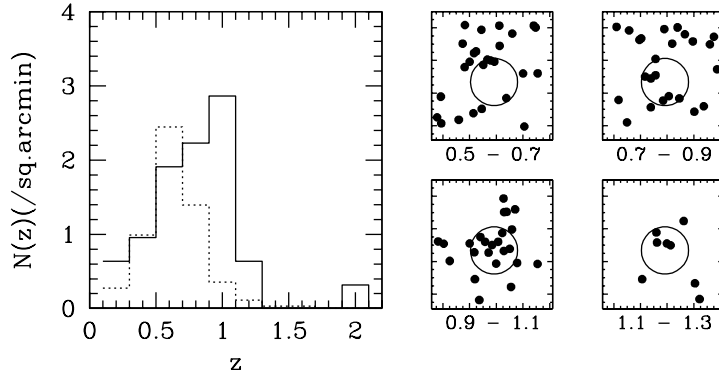


Figure 2: Left panel shows the photometric-redshift distribution for galaxies with available multi-color data (solid histogram) in one of the cluster fields. Also shown is the redshift distribution for background galaxies (dotted histogram). The four panels in the right show the projected distribution of galaxies in 0.2 redshift bins. The field is roughly  $5 \times 5$  arcmin and the circle represents the expected size of a cluster at this redshift.

we have resorted to the same method employed above in analyzing color slices, but considering redshift slices. We find that in six out of the seven cases analyzed so far a concentration is detected. Figure 2 illustrates the distribution of galaxies brighter than  $I = 22$  in photometric redshift slices 0.2 in width, for one of the cases considered. An overdensity of galaxies is clearly seen in the redshift interval 0.9-1.1, which coincides with the position obtained by employing the matched-filter algorithm which, by the way, also predicts  $z_{MF} \sim 1$ . More importantly, from these redshift estimates individual galaxies can be selected for spectroscopic observations over a much larger area than that covered by early-type galaxies detected using a single color criterion.

### 3 Analysis of Spectroscopic Data

The spectroscopic data are from observations conducted at the 3.6m telescope at La Silla using the EFOSC2 spectrograph [19] [7] and from a single 3 hours test exposure using the 2dF spectrograph at AAT [5]. The EFOSC2 observations yielded 69 redshifts in the field of seven EIS cluster candidates selected in the redshift interval  $0.5 \leq z_{MF} \leq 0.7$ . The observations conducted at the 2dF cover

the vicinity of 58 cluster candidates in Patch D, nearly all of the clusters over about two-thirds of the total area of the *I*-band survey, irrespective of their estimated redshift. A total of 340 galaxies were observed yielding 197 redshifts.

A likelihood analysis of the redshift distribution of the galaxies observed with EFOSC2 was performed, based on a comparison with results obtained from random re-sampling of the CFRS redshift distribution. This analysis has shown that four of the seven systems correspond to a real system in redshift space with a probability  $> 95\%$  [19]. Two of them have a mean redshift in agreement with  $z_{MF}$ , while the other two have significantly smaller redshifts. However, it is important to note that the redshift distribution in each cluster field is under-sampled and the identification of bound systems from the redshift distribution alone may not suffice for a conclusive determination about the nature of the system and its redshift. In this case it is important to take into consideration other constraints such as the detection of overdensities in color slices, the spatial distribution of galaxies with measured redshifts and their brightness. Therefore, we supplement the above spectroscopically confirmed sample with systems for which an overdensity of red galaxies is detected and at least one galaxy along this red-sequence has a measured redshift. When these cases are considered three additional clusters are identified with redshifts much closer to those estimated by the matched-filter. In one case, even though only one redshift is available, it corresponds to the brightest galaxy in the field. Moreover, this galaxy lies on a clearly visible red-sequence, consistent with the measured redshift ( $z = 0.81$ ) [7]. Furthermore, in one case the low redshift assigned by the likelihood analysis is very likely due to the superposition of a nearby system, since one of the measured redshifts is consistent with that inferred from the color analysis and with that estimated by the matched-filter. When combined, all the information available suggests that all seven clusters can be confirmed and, with exception of one, all observed candidates have  $z \gtrsim 0.5$ . Clearly, denser sampling of these fields is required to resolve some of these ambiguities.

While no detailed analysis has been carried out of the accumulated 2dF data, the completeness of this preliminary survey as a function of magnitude immediately indicates that only clusters with  $z \lesssim 0.4$  can be identified from the redshifts. From a preliminary inspection of the redshift distribution, identifying cases with two or more concordant redshifts and, as discussed above, by examining measured redshifts and color detections, we find that for 22 candidates, corresponding to 60% of those with  $z < 0.4$ , it is possible to tentatively assign a spectroscopic redshift to the cluster.

Combining all the available spectroscopic data we can assess how well the redshift estimated by the matched-filter reflects the true redshift. In Figure 3, we compare the median of the measured redshift distribution to the original  $z_{MF}$ . Error bars again represent the full range of the distributions. The results show that the matched-filter redshift is indeed a fair indicator of the cluster redshift at least out  $z_{MF} \sim 0.7$ . On average it overestimates the redshift by  $\Delta z \sim 0.1$ , comparable to the observed scatter. Even though these preliminary results are

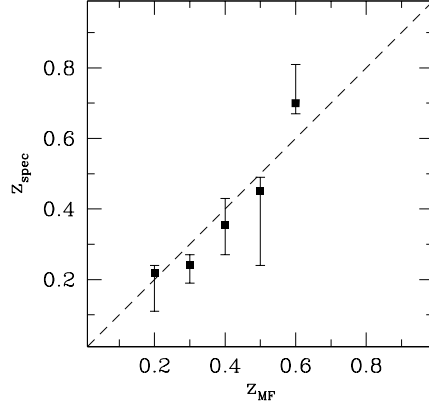


Figure 3: The relation between measured and estimated redshift for the clusters with spectroscopically assigned redshifts.

admittedly based on a small sample they are encouraging since most of the candidate clusters observed were drawn directly from the matched-filter list without any prior information.

## 4 Conclusions

In this paper we have investigated the reality of the  $I$ -band selected EIS cluster candidates over an extended redshift baseline. Our main findings are:

1. For most cluster candidates with  $z_{MF} \lesssim 0.4$ , red-sequences can be clearly seen in the  $(V - I) - I$  CM diagram leaving little doubt that they are real clusters.
2. The success rate of detecting concentrations of red galaxies is  $\gtrsim 70\%$  out to  $z_{MF} \sim 0.8$ , dropping to about 40% at  $z_{MF} \sim 1$ .
3. There is a clear correlation between colors and the redshift estimated by the matched-filter algorithm. This correlation is seen up to  $z_{MF} \lesssim 0.7$  when the  $(V - I)$  color is used and up to  $z_{MF} \sim 1$  when  $(I - Ks)$  is considered. The color-redshift relation is consistent with models of stellar population evolution and/or the color measured for elliptical galaxies in clusters with measured redshifts.
4. Preliminary spectroscopic observations show that the measured redshifts are consistent with those estimated by the matched-filter algorithm

With the estimated success rate from spectroscopy at  $z < 0.6$  and from imaging for larger redshifts we have demonstrated that large samples of clusters are



within reach comprising low ( $z \gtrsim 0.2$ ) to very high-redshift clusters ( $z \sim 1$ ). Such a sample would be ideal for evolutionary studies of galaxies and large-scale structures. The EIS cluster catalog being compiled will also be of great value for many other applications and in support to VLT observations as well as targets for follow-up observations with Chandra and XMM. There is currently no comparable sample in the southern hemisphere.

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